POTENTIAL AND LIMITATIONS OF MULTI-TEMPORAL SAR DATA IN A QUANTITATIVE APPROACH FOR MULTI-SCALAR HYDROLOGICAL APPLICATIONS.
SYNTHESIS OF ERS ALSACE/CAMARGUE PILOT PROJECT.

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ABSTRACT

The potential of multi-temporal ERS SAR data in hydrological applications is investigated in two areas - the Alsace and Camargue regions - where wetland and flood monitoring analysis are performed. In the Alsace test site, a large data base has been built up in order to dissociate and analyse the different factors influencing the ERS backscattering coefficient. Firstly, a review of the different findings is summarised showing that: 1) At a regional scale, there is a strong correlation between ERS-1 SAR backscattering coefficient and a soil moisture parameter; 2) A minimum spatial scale can be defined at which the backscattering coefficient measurement of ERS can be achieved with a given level of confidence in order to derive quantitative bio-geophysical information. Then, in order to determine the optimal conditions for soil moisture retrieval using ERS SAR data, the influence of vegetation parameters has been analysed. The NDVI, derived from synchronous SPOT imagery for different classes of cropland and grassland, was used to estimate different vegetation states. The study of the spatial and temporal backscattering coefficient's behaviour vis-à-vis the vegetation state, over a multi-year period, allows the determination of an empirical relationship between those parameters to be determined. In the Camargue Region, high temporal ERS acquisitions, recorded in a 3-day mode before, during and after the 1993 and 1994 floods, are used to evaluate ERS SAR data potential in flood detection and monitoring. Additionally, the ERS SAR data acquired after the 1994 flood, are used for the study of the backscattering coefficient's temporal behaviour with respect to the hydrological state of the soils (i.e. flooded, saturated, moist). This study permits a trend curve, relating the ERS backscattering coefficient and the hydrological state of the soils, to be established.

1. INTRODUCTION

Since the launch of ERS-1, several studies have shown experimental results relating ERS-1 SAR backscattering coefficient to a number of land surface bio-geophysical parameters (Bouman and Uenk, 1992 ; Demircan *et al* ., 1993 ; Wooding *et al.*, 1994). With its system configuration parameters (C-band, VV polarisation) and an incidence angle of 23°, the use of ERS-1 SAR should provide near optimal sensitivity to soil moisture in combination with a minimal sensitivity to surface soil and vegetation roughness (Ulaby, 1974). Intensive theoretical and experimental studies have been conducted with the results showing a strong correlation between the ERS backscattering coefficient and soil moisture (Wooding *et al.*, 1993; Fellah *et al*., 1994; Le Toan *et al*., 1994; Mohan *et al.,* 1994). In order to determine the optimal condition for soil moisture retrieval, the other factors influencing the backscattering coefficient have to be taken into account. In fact, several studies (Ulaby *et al.*, 1976; Attema *et al.*, 1978; Wang 1985; Prevot *et al.*, 1993) have shown that an estimation of the soil water content can be derived for grassland and cropland under specific conditions (flat terrain, surface roughness, biomass, ...).

Within the ESA pilot project AO2-F122, sponsored by the CNES and the Conseil Régional d'Alsace, a study aiming to evaluate the potential of multi-temporal ERS data for hydrological applications during normal and exceptional hydrological conditions in the Alsace plain and Camargue Region, has been carried out.

In the Alsace plain, a quantitative approach for soil moisture retrieval was investigated. After a short review of the main results obtained previously and which have already been published (Fellah *et al.*, 1994, 1995a), a study of the influence of the vegetation parameters on the backscattering coefficient was performed in order to define the optimal conditions for soil moisture retrieval. This work was performed within a Geographical Information System using an extensive multi-source regional data base.

In the Camargue region high temporal flood zone detection and monitoring using ERS data, acquired in 3 mode, during the exceptional hydrological conditions of 1993 and 1994, was performed. This study pinpointed the usefulness of ERS SAR data in the precise cartography of flood limits and therefore, in the provision of flood dynamic information (Tholey *et al.*, 1995; Laugier *et al*., 1997). A second objective, which is presented hereafter, was to analyse the temporal backscattering coefficient's behaviour over zones which pass from flooded to different moisture states during soil drainage. This was done by using ERS SAR data acquired with a 3-day cycle after the flood event in January 1994.

2. THE ALSACE TEST SITE

The study area, the Ried Centre Alsace, is situated between Strasbourg and Colmar on the Alsace plain (North-eastern France). It is a very flat area and an environmentally sensitive biotope which is strongly influenced by hydrological processes and is therefore affected by new EU environmental and CAP directives. The landuse in this region comprises intensive agriculture which consists essentially of corn but also areas of grassland.

2.1. DATA BASE

A large regional database was developed aimed at isolating information which relates to soil moisture by dissociating and analysing the importance of the numerous parameters that affect the SAR signal return. The data base contains calibrated ERS-1 SAR and optical satellite data, plus exogenous data, all integrated within a GIS.

ERS-1 data

More than thirty essentially springtime or autumnal ERS-1 images were selected between 1991 and 1995. These periods are interesting as these seasons reflect contrasting hydrological regimes. Meteorological data was used in choosing ERS-1 scenes enabling the differentiation between moisture due to rainfall and that caused by other factors (soil moisture retention, water table, etc.).

Optical satellite data

SPOT XS scenes, which are quasi-synchronous to ERS SAR acquisitions, acquired between 1991 and 1995, allowed the realisation of a precise landuse classification. This thematic classification allowed the spatial and temporal ERS backscattering coefficient to be analysed per landuse.

Exogenous data

There are comprised of a DTM, scanned cartographic data (piezometric, pedological and substrate deposits data), providing information on the natural environment, administrative cadastral coverage, meteorological information and, particularly, mapped antecedent precipitation indexes prior to ERS acquisitions. These were complimented by synchronous aerial photos and field surveys.

2.2. QUANTITATIVE MEASUREMENTS OF BIO-GEOPHYSICAL PARAMETERS

A review of the different stages of this study is summarised below. The radar's backscatter behaviour relating to different land covers is studied. Then, the sensitivity of ERS SAR data to soil moisture variation is investigated. The impact of observational scale on SAR radiometric resolution is analysed. Finally, the results of the influence of the vegetation parameters on the backscattering coefficient are presented in more detail.

The backscattering coefficient has been calculated using the method described by Laur *et al.* (1992, 1996). In order to enable the comparison of backscattering coefficients obtained for all scenes, it is important to ascertain the spatial and temporal calibration of the ERS signal and the influence of the incidence angle per theme considered. A test was therefore performed for several land cover types taken from a multitemporal SPOT XS classification on two ERS-1 scenes acquired 12 hours apart with no rainfall being recorded within the time interval. In this case, no change in the landscape is assumed. The backscattering coefficient calculated for the grassland, cropland and forest themes on both ERS-1 images is calculated with an excellent backscattering measurement stability being noted (less then 0,15 dB variation). It is therefore possible to define a temporal thematic signature for each theme taken into account.

2.2.1 Effect of landcover on the backscattered signal

An analysis of backscattering coefficient's temporal variations vis-à-vis the following landcover themes, forestry, grasslands and croplands was carried out between Spring 1992 and Autumn 1993 by using 12 ERS-1 data sets. Forestry's backscattering coefficient is practically stable at -7.7dB +/-0.2dB. Between Spring and Autumn, the backscattering coefficient for both grassland and cropland rises respectively by 2dB and 3dB. These seasonal variations are, in particular, explained by the evolution of the vegetal cover between Spring and Autumn. A backscattering coefficient variation for the grassland and cropland themes was also observed in the case of temporally close acquisitions (a few days) for which landuse would have not changed. The reason for these variations is most likely linked to soil moisture variations due to rainfall.

2.2.2 Sensibility of ERS-1 SAR data to soil moisture variation

A first study aiming to test the sensitivity of ERS SAR backscattering coefficients was carried out. For this purpose, rainfall prior to SAR acquisitions was spatialised by using information provided by METEO FRANCE from 27 rain gauges in the study area. The backscattering coefficient was calculated over bare soil and short grassland in relation to the gradient of antecedent precipitation index. A strong correlation was shown between the ERS-1 SAR backscattering coefficient for bare soil (0.94) and short grassland (0.92), calculated at a regional scale, with soil moisture being linked to recent plotted rainfall events. The results, as obtained, open interesting fields of applications for large scale hydrological applications and inversion algorithms are therefore being investigated. Furthermore, this study points out that, due to the statistical properties of speckle in SAR imagery and the effect of local parameters, the accuracy level of the soil moisture estimate depends on the scale at which the backscattering coefficient is determined and therefore seems to create limitations for local scale applications.

2.2.3 Impact of observation scale on backscattering coefficient measurement accuracy

In order to test the potential and limitations of ERS-1 SAR in local to global scale applications, the impact of observation scale on SAR radiometric resolution and therefore on the level of accuracy of soil parameter estimation has to be investigated. A relationship between the observation scale and the accuracy of the backscattering measurement has been established and validated in the case of ERS-1 SAR data (Bally and Fellah, 1995). Taking into account the user requirements in terms of measurement accuracy for soil moisture estimation, this relationship permits a minimum spatial scale to be calculated for which the quantification of the soil parameter can be determined at a sufficient confidence level. There is therefore a limitation of the use of ERS SAR data in estimating a soil moisture parameter, or any other parameter, at local scales (Fellah, 1995b). For example, considering the theoretical and experimental results obtained by Borgeaud (1993), who concludes that to retrieve soil moisture information to a 5% accuracy a backscattering coefficient precision of +-0.5 dB is necessary. The use of the relationship derived above between observation scale and backscattering coefficient measurement accuracy leads to a minimal spatial scale of 3.5 hectares.

2.2.4 Influence of vegetation parameters on the ERS Radar Backscatter

The analysis of the vegetation parameters influence on the backscattered signal is investigated for Spring seasons, during crop grown, with ERS SAR data acquired between 1991 and 1993. The NDVI derived from SPOT data, which are quasi-synchronous to processed ERS SAR acquisitions, is used to estimate different vegetation states. The NDVI is calculated for all the SPOT data using Equation 1 below:

$$\mathrm{NDVI} = [\ [\ (XS3 - XS2)\ /\ (XS3+XS2)\ ] + 1\ ] * 128. \qquad (1)$$

For each SPOT image, the mineral/vegetal threshold was calculated, the retained NDVI value is 159 for all the data. The NDVI values included between the mineral/vegetal threshold and the maximum are grouped into about ten different classes, each class for 5 NDVI values (Table 1). These classes enable the biomass of vegetation for cropland and grassland to be estimated.

Classes	Intervals
1	159-163
2	164-168
3	169-173

4	174-178
5	179-183
6	184-188
7	189-193
8	194-198
9	199-203
10	204-208

Table 1: NDVI classes

The backscattering coefficient is calculated for these two themes, for each NDVI class and for each ERS-1 SAR image. As an example, Figure 1 shows the backscattering coefficient behaviour for cropland and grassland relating to NDVI classes calculated with a SPOT scene acquired the 17/05/92, which is quasi-synchronous to the Spring ERS SAR image acquired on the 22/05/92.

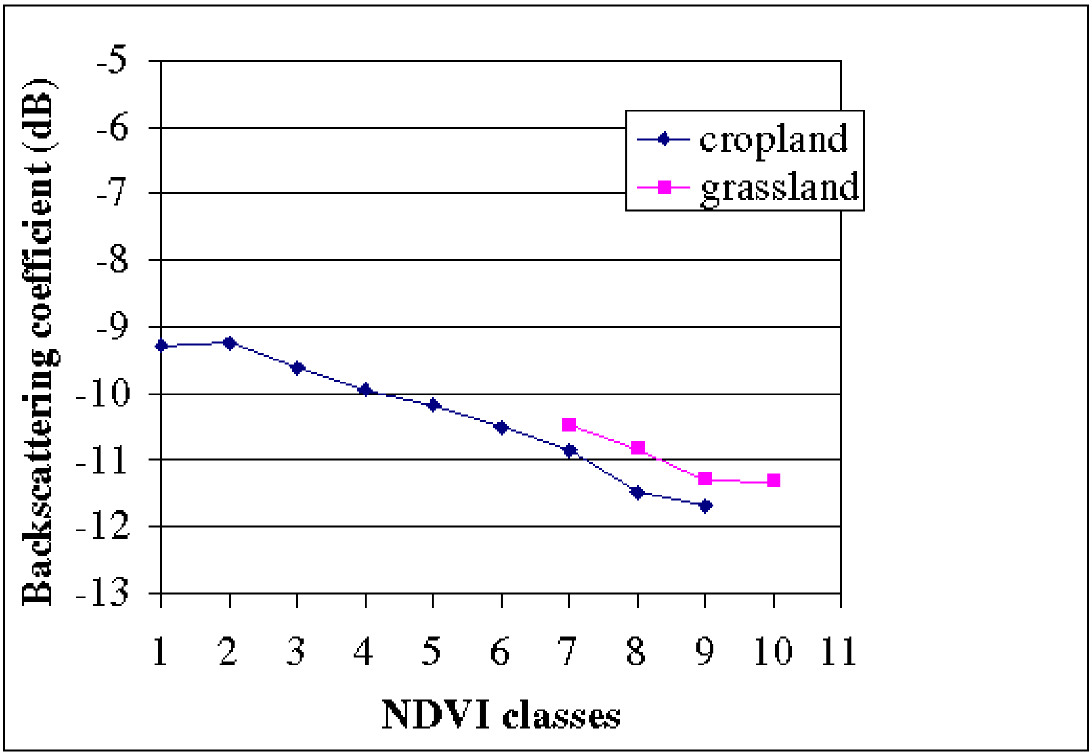

Figure 1: Behaviour of the backscattering coefficient calculated using 22/05/92 ERS SAR data with respect to NDVI classes calculated using 17/05/92 SPOT data

Correlation between NDVI classes and Radar backscatter

Figure 1 shows that there is a linear relationship between ERS backscattering coefficient and NDVI classes, and that the backscattering coefficient is slightly different for cropland and grassland which have the same NDVI values. This last point shows that complementary information from ERS SAR data could be derived about vegetation parameters (structure and/or water content).

The same linear decline of the backscattering coefficient with respect to NDVI (Radar backscatter decrease is about 2dB between minimal and maximal NDVI classes) is found for croplands in all the acquisitions recorded during the Spring period. This is only the case when rainfall effects on the backscattered signal are negligible and when the SAR and optical acquisitions are sufficiently synchronous. Therefore, using 6/05/92, 22/05/92 and 26/05/93 measurements, a relation between the backscattering coefficient and NDVI was investigated. A linear regression was found with a correlation coefficient greater than 0,92 for these three dates (figure 2).

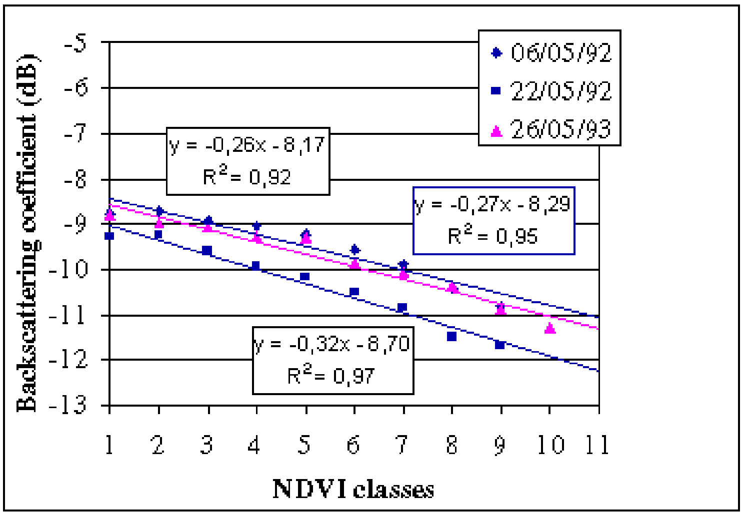

Figure 2: Behaviour of the backscattering coefficient calculated using 06/05/92, 22/05/92 and 26/05/93 ERS SAR data with respect to NDVI classes calculated using 17/05/92 and 18/05/93 SPOT scenes and their respective linear regressions.

These correlations show that an empirical relation between NDVI classes and the ERS backscattering coefficient can be established in this area for agricultural lands. The inversion and the spatialisation of this parameter over agricultural lands using ERS SAR data can therefore be carried out and is currently being investigated.

3. THE CAMARGUE TEST SITE

Located in the delta of the Rhône river in the South of France near the town of Arles, the Camargue region is a very flat plain normally protected from Rhône floods by embankments. A few months after the October 1993 flood, the Camargue region was flooded again in January 1994 after the formation of breaches in the Rhône river dykes. During the flood-level rise, Rhône water spread successively from breaches to the four Camargue flood basins (Vianet, 1994). These flood basins are the Saliers, Tête de Camargue, Bernacles and Grand Mar basins.

Within this project, the potential of multi-temporal ERS SAR data, during exceptional hydrological conditions, for flood detection and monitoring was presented by Laugier *et al.,* 1997. In the following section, an analysis of the backscattering coefficient's behaviour during soil drainage, which followed the 1994 Camargue flood, is presented.

3.1. THE DATA BASE

A data base has been built up in order to acquire historic background knowledge concerning the 1994 Camargue flood and to acquire information concerning the natural environment of the Camargue region. This data base is composed of satellite and exogenous data.

Satellite Data

The satellite data include a SPOT XS scene plus fourteen ERS-1 SAR scenes acquired before, during and after the 1994 flood. These scenes were acquired during a three day ERS-1 acquisition mode (phase D). The SPOT XS scene was acquired on the 26th of March 1993 and was used to derive landcover information. The ERS data were acquired between the 3rd of January 1994 and the 16th of March 1994.

Exogenous data

The exogenous data include topographic, pedological and soil maps as well as meteorological information and a flood report (Vianet, 1994). The meteorological data, which include daily precipitation for the period lasting from December 1993 to March 1994, were recorded by METEO FRANCE at the Tour du Valat station located in the Camargue region.

3.2. RADAR BACKSCATTER BEHAVIOUR DURING SOIL DRAINAGE

The backscattering coefficient's behaviour was analysed over surfaces during soil drainage after the flood. This allows the description of the backscattering coefficient's behaviour on surfaces at different hydric states during the transition from saturated to moist soil states. In fact, over a range from typically 10-40% soil moisture content, most studies show a linear increase and correlation between the backscattering coefficient and soil moisture. In the case of very moist or saturated soil, the backscattering coefficient's behaviour is not well known. This knowledge is nevertheless important especially in the study of wetland evolution, which frequently comprise very moist soil near saturation point. Two studies (Merot and Chanzy, 1991; Brun *et al*., 1990) had shown that the backscattering coefficient, calculated using sensors with similar parameters as ERS-1 (i.e. wavelength, polarisation and incidence angle), increases when soils pass from a flooded to a moist state.

3.2.1 Approach for the backscattering coefficient measurements

The backscattering coefficient was calculated using the method described in Laur *et al.,* (1996). In order to study the backscattering coefficient's behaviour during soil drainage, measurements were done per image (every 3 days) and per ''flood ring''. Flood rings are defined as zones which are included between two consecutive flood zone limits (Fig. 3). These limits result from the cartography of the 1994 Camargue flood established using multi-temporal ERS SAR images and auxiliary information as detailed in Laugier *et al*. (1997).

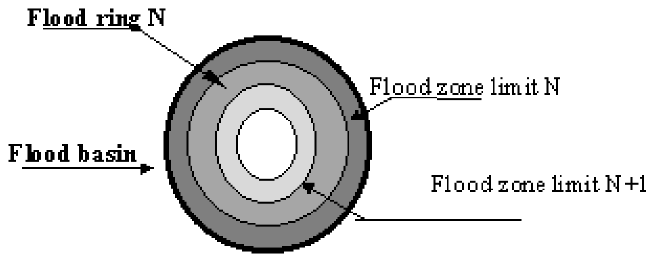

Figure 3: Principle of the "flood ring"

Measurements are performed for the four basins together and individually as they could have their own hydrological characteristics.

As a first step, the backscattering coefficient measurements were carried out on 3 large reference fields (more than 3 hectares). These fields comprised one grassland and two rice fields located in agricultural zones within the Camargue region but outside flood zones. The figure 4 shows the temporal behaviour of the backscattering coefficient related to ERS-1 SAR acquisitions. Histograms of rainfall amount are also superimposed on this figure. For the reference fields, the trend of the curves is globally the same. One can also notice that globally their peaks follow important rainfalls and that radar backscatter decreases during dry periods, showing again, the effect of rainfall events in the ERS backscatter signal.

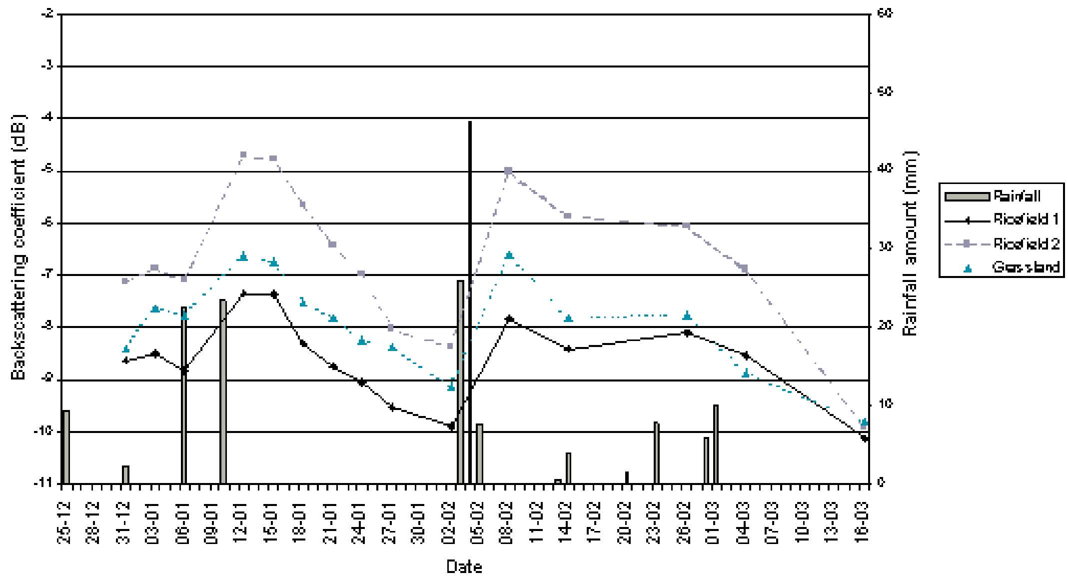

Figure 4: Temporal backscattering coefficient behaviour in the reference fields.

3.2.2 Analysis of the backscattering coefficient's behaviour during soil drainage

The temporal behaviour of the backscattering coefficient in each flood ring, for respectively, the ensemble of basins and independently for the 4 individual basins was analysed. Between each acquisition, separated by only 3 days, the landscape is considered constant The surface which are considered within each flood ring consists of agricultural land without vegetation cover. Surface roughness and soil maps have been considered in the analysis of the temporal backscattering coefficient's behaviour, but it has been shown that under this experimental conditions, soil moisture was the predominant dynamic factor and therefore had the predominant effect on the backscatter signal analysis. Figure 5 shows the temporal backscattering coefficient's behaviour per flood ring for the basin set. The Bernacles basin is taken as an example to illustrate the analysis per flood basin (Figure 6). In fact, the behaviour of the backscattering coefficient in the other flood basins is very similar except for the Grand Mar basin. The difference in the Grand Mar basin is explained by the land cover, which is essentially composed of natural marshlands contrary to the other flood basins, which are agricultural areas without vegetation cover. Due to the presence of marshlands in the Grand Mar flood basin, the backscattering coefficient's measurements from this basin will not be discussed further.

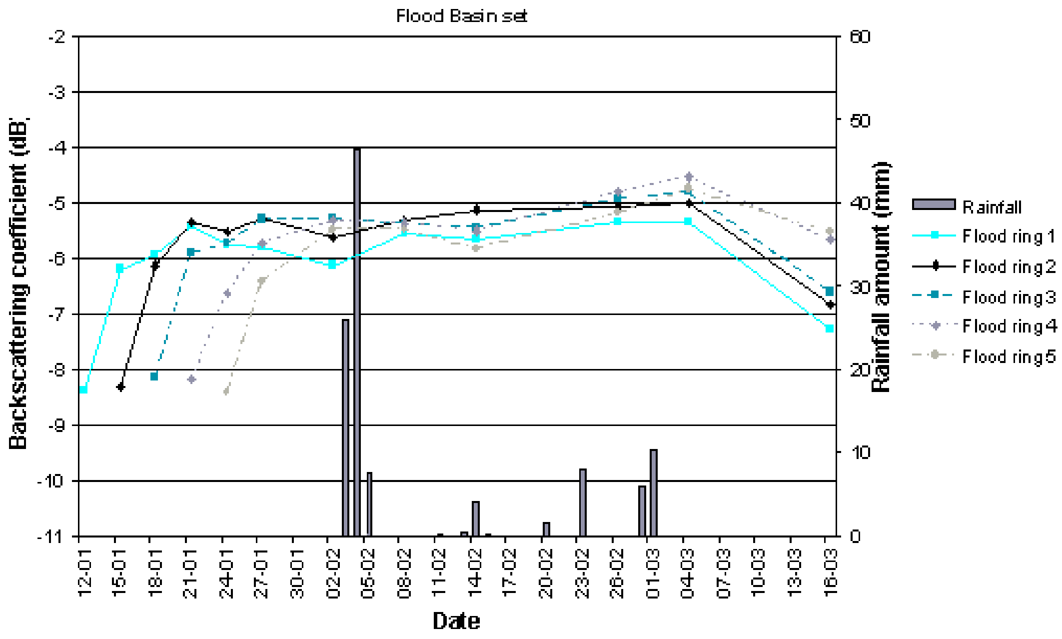

Figure 5: Temporal backscattering coefficient behaviour in each food ring for the ensemble of basins.

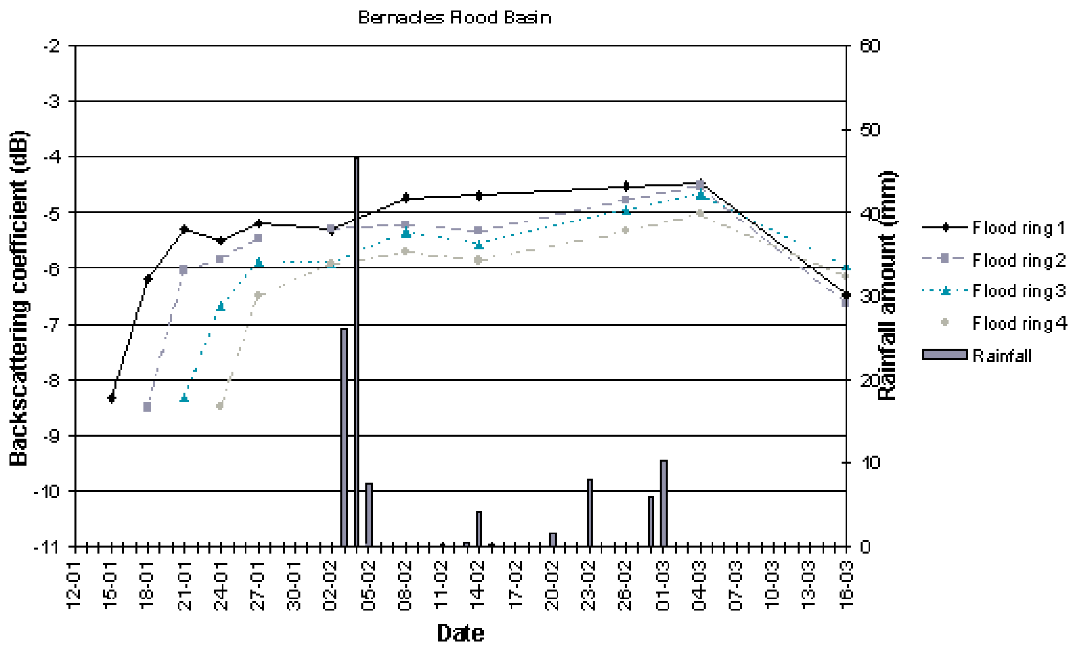

Figure 6: Temporal backscattering coefficient behaviour in each food ring for the Bernacles basin.

In Figure 5 and 6, the backscattering coefficient increases when the area of the flood rings pass from flooded to saturated and moist. One can note that contrary to the reference fields, the rainfall in the period between the 2nd and 5th of February do not correspondingly increase the backscattering coefficient value calculated over the flood rings. This means that an increase in soil moisture for very wet surfaces does not automatically mean an increase in the backscatter signal.

The temporal backscattering coefficient's behaviour for the flood basin set and the Bernacles flood basin versus time interval since the start of soil drainage are respectively presented in Figures 7 and 8. In order to avoid rainfall influence on the backscattering coefficient, the measurements used stop before the 2nd of February. The curve trend of Figure 7 and 8 clearly shows that the backscattering coefficient increases as an asymptotically towards a peak situated between -5dB and -4 dB before becoming stable or diminishing slightly.

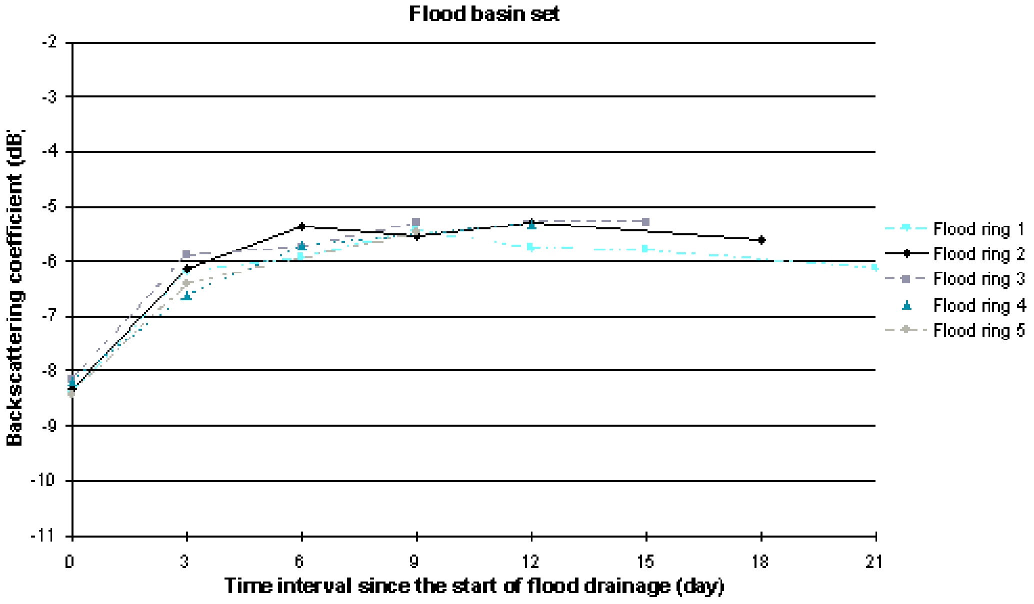

Figure 7: Backscattering coefficient behaviour in each food ring with respect to time interval since the start of flood drainage for the ensemble of basins.

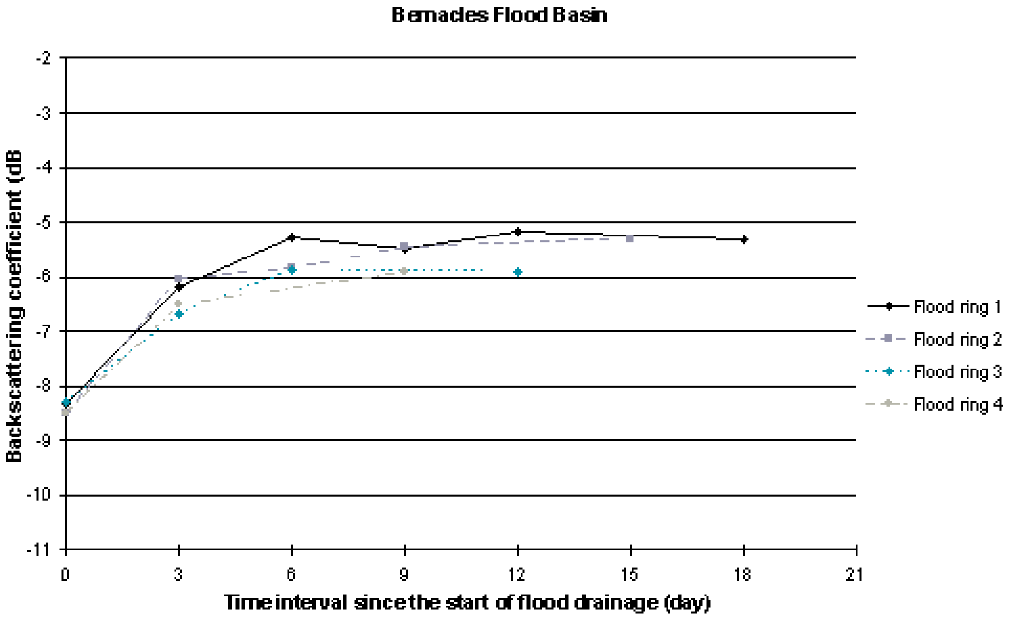

Figure 8: Backscattering coefficient behaviour in each food ring with respect to time interval since the start of flood drainage for the Bernacles basin.

Trend curve elaboration and discussion

The analysis of the temporal behaviour of the backscattering coefficient's during soil drainage enables a trend curve to be drawn, showing the backscattering coefficient behaviour versus the hydric state of the soil.(Fig. 9)

The main remarks to be made following this analysis are that firstly, a soil under two different hydrological states could have the same backscattering coefficient and secondly, after a certain soil moisture level the backscattering coefficient increases asymptotically.

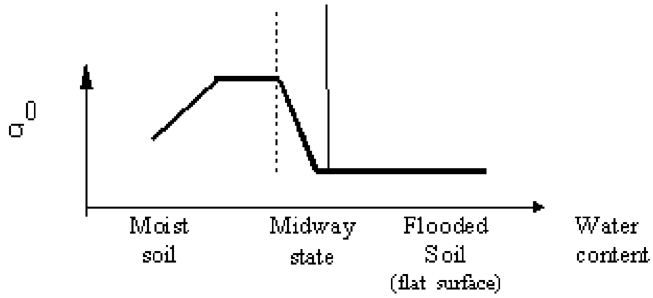

Figure 9: Trend curve showing the backscattering coefficient (s ^{0}) with respect to soil hydrological states

4.CONCLUSION

The work carried out in these two regions using multi-temporal ERS SAR data together with auxiliary information has led to main results listed below:

In the Alsace test site where a quantitative approach towards soil moisture retrieval was carried out, the work has shown that:

There is a strong correlation between the ERS SAR backscattering coefficient calculated over large surfaces and soil moisture content. This has been noted for bare soils and short grassland during the Spring period.

A springtime multi-year study on the ERS backscattering coefficient versus an NDVI derived from synchronous SPOT data allows an empirical relationship between those parameters to be determined in this region. This can be used to determine the optimal conditions for soil moisture retrieval using ERS SAR data and pinpoints the potential of SAR data for the evaluation of vegetation parameters.

A relationship between SAR radiometric resolution and observational scales has been investigated, established and validated in the case of ERS-1 SAR products. This permits the determination of a minimum spatial scale at which the backscattering coefficient measurement can be achieved with a given level of confidence in order to derive quantitative bio-geophysical information. This pinpoints therefore some limitations in the use of ERS SAR data in quantifying bio-geophysical parameters at local scale.

In the Camargue region, 3 day mode ERS SAR data acquired before, during and after the 1993 and 1994 floods were processed. This study shows the high potential of ERS SAR data in the precise cartography of flood mapping and therefore in the provision of flood dynamic information. Furthermore, the analyse of the backscattering coefficient’s behaviour during soil drainage has enabled the building up of a trend curve showing the backscattering coefficient’s behaviour with respect to different soil hydrological states.

This study has underlined important aspects that must be considered in applications of ERS SAR data. The implications of this study open interesting perspectives in the field of hydrological ERS applications, as it seems that useful information could to be extracted at a regional scale and therefore open environmental applications for example in the wetland studies domain. In addition, the use of ERS SAR data during exceptional hydrological conditions demonstrates that operational use of this data can be envisaged in flood applications.

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